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A delayed flowering barrier to higher soybean yields

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Abstract

A long term maximum yield soybean [*Glycine max* (L.) Merr.] research project was initiated at Wooster, OH (40°N latitude) in 1977 with the specific objectives of determining the yield potential of soybeans and identifying yield limiting factors. Results from this research suggest there is a delayed flowering barrier to higher soybean yields in the higher latitudes where the light intensity (sun angle) is highest and the day length is longest early in the growing season, declining as the growing season progresses. At Wooster, OH, the average 24 h total solar radiation declines from 474 Langleys (cal/cm^2) in June to 351 Langleys in September. The maximum daily solar energy declines from 680 Langleys (15–30 June) to 444 Langleys 15–30 September. Under normal spring temperatures in May, soybeans planted during the first week of May normally bloom during the first week of July. However, in 1982, 1985, 1998, and 1999, unusually early warm spring temperatures in May resulted in the soybeans flowering around 15 June, 2 weeks earlier than normal. In a maximum yield environment, where all manageable yield limiting factors were minimized, test average yields were 5963 kg/ha in 1982, 5549 kg/ha in 1985, 5383 kg/ha in 1998, and 5416 kg/ha in 1999, with individual lines producing replicated yields in the 6000–7000 kg/ha range. In the intervening years, 1983 and 1984 and from 1986 to 1997, with more normal spring temperatures, test average yields in the maximum yield environment ranged from 3575 to 4862 kg/ha, with highest yielding individual lines producing yields in the 4200–5500 kg/ha range. These results indicate there is a temperature by photoperiod interaction in soybeans that results in soybeans flowering up to 2 weeks earlier than normal in response to above normal temperatures in early spring (in May at Wooster, OH). This results in the soybeans entering the reproductive cycle earlier in the growing season when the days are longer and the light intensity is higher (greater total solar radiation is available). Also the length of the reproductive cycle was increased since maturity was similar to years of more normal spring temperatures. This resulted in a significant increase in the yield potential of soybeans in years of unusually early warm spring temperatures. These results suggest if breeders can develop full season soybean cultivars that will bloom earlier under more normal spring temperatures, the yield potential of soybeans in the higher latitudes could be significantly increased.
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1. Introduction

In the late 1960s (1966–1968), National Soybean Yield Contests were held in the US. The generally accepted yield limit for soybeans prior to the 1966 yield contest was in the 4000–4500 kg/ha range. The soybean research community was astounded when two growers obtained 6000 kg/ha in the 1966 National Soybean Yield Contest (Table 1). In 1967 the five top growers had yields in the 6000 kg/ha range, and in 1968, four growers reported yields in excess of

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Table 1
1966–1968 national soybean contest yield records

Year	Yield (kg/ha)
1966	
Pick, Chenoa, IL	6203
Beason, Hamburg, IA	6203
Van Dyke, Trenton, TN	5269
Lefferdink, Firth, NE	5009
Huser, Neodesha, KS	4809
1967	
Chandler, Herrick, IL	6350
Storeholder, Delta, OH	6283
Kimmons, Ozark, MO	6170
Harms, Allison, IA	6030
Jacks, Thornton, MS	6010
1968	
Kimmons, Ozark, MO	7310
Tarnow, Rolling Prairie, IN	6890
Pick, Chenoa, IL	6717
Peeler, Union, NE	6710
Glaser, Stewart, IL	6497

Table 2
Highest yields reported from soybean maximum yield research

Location	Researcher	Year	Yield (kg/ha)
New Jersey	Flannery	1980	6270
		1981	6203
		1982	7270
		1983	7911
Ohio	Cooper	1982	6817
		1985	6710
		1998	6050
		1999	6443
Australia, Qld	Lawn et al.	1984	8004
		1984	8604

6700 kg/ha, with a record 7310 kg/ha by the contest winner. Understandably, there was considerable skepticism about the legitimacy of these exceptional yields.

In the scientific community a question being asked was, ‘‘if these high yields are possible, why have not they been obtained in replicated research plots?’’. These contest yields stimulated some researchers, including the author, to determine if such high yields might be obtained in replicated research plots. Using a maximum yield research approach, where all manageable yield limiting factors, such as water, soil fertility, lodging, row spacing, seeding rate, and pest control are minimized, three researchers (PPI (Flannery), 1983a, 1984; PPI (Cooper), 1983b; Lawn et al., 1984) have since reported soybean yields in excess of 6700 kg/ha (Table 2).

These results suggest the reason contest winners were the first to break the 6700 kg/ha yield barrier was the lack of a maximum yield research approach by soybean researchers. Failure to recognize the lodging barrier to higher soybean yields was a major factor limiting research plot yields (Cooper, 1971a,b; Woods and Swearingen, 1977). Whenever the environment was favorable enough (adequate rainfall) to produce 6000+ kg/ha yields, the then currently available cultivars severely lodged, limiting their yield potential. In contest winner's fields, with hundreds of contestants, some growers had the rare combination of adequate water for these high yields without lodging. In many cases, these record yields were obtained on river bottom soils with a high water table or under irrigation, avoiding the need for water from rainstorms that would lodge the crop. Research in Japan, where soybeans were grown in rice paddy lands and the soil was built up around the stems to prevent lodging, 6500 kg/ha yields have been obtained (Spaeth et al., 1987). These high yields were recently duplicated in the 1997 Nebraska State Irrigation Yield Contest with a reported yield of 6660 kg/ha. The theoretical biological limit for yield in soybeans has been estimated at 8000 kg/ha (Specht et al., 1999).

In addition to the lodging barrier to higher soybean yield, row spacing and seeding rates have also been identified as yield limiting factors in high yield environments (Cooper, 1977; Cooper and Jeffers, 1984; Costa et al., 1980).

In recognition of these yield limiting factors, determinate semidwarf cultivars (Cooper, 1981, 1985) and shorter, more lodging resistant indeterminate cultivars have been developed, and solid seeding of soybeans in 175 mm row spacing has become a widely accepted soybean production practice. However, in spite of the maximum yield research approach, practiced in a long term experiment at Wooster, OH, consistent 6000–7000 kg/ha yields have not been possible (Cooper, 1989a,b; Cooper et al., 1991, 1992).

It was noted that the higher yielding years were associated with unusually early warm spring temperatures that triggered earlier flowering in the soybeans, suggesting an interaction between photoperiod and temperature, a photo/thermal effect. The effect of the interaction between photoperiod and temperature on the time of flowering in soybeans was first reported by Garner and Allard (1930) with higher temperatures resulting in earlier flowering. There has been extensive research on the effect of temperature and photoperiod, and the interaction of temperature and photoperiod, on the phenology of soybeans with specific interest on days from sowing to first flower (Major et al., 1975; Summerfield et al., 1993; Hadley et al., 1984; Upadhyay et al., 1994; Piper et al., 1996; Cober et al., 2001). The objective of these studies was to develop equations using temperature and photoperiod functions to predict the phenology of soybeans. These studies indicate higher temperatures during the sowing to flowering period result in earlier flowering.

Using maturity isolines of the soybean cultivar, Clark, Upadhyay et al. (1994) reported that the eight isolines did not differ in the sensitivity of the flowering response rate to temperature but differed considerably in sensitivity to photoperiod. Therefore, they concluded temperature sensitivity of the flowering response is under separate genetic control than photoperiod sensitivity. Although in most studies, higher temperature results in earlier flowering, in a recent study (Cober et al., 2001), using maturity gene isolines of the soybean cultivar, Harosoy, they observed that the late flowering isolines flowered earlier under cooler temperatures, suggesting that there may be genes present in soybeans which promote earlier flowering under cool conditions. These results suggest breeding for soybean cultivars that will flower earlier under cooler spring temperatures should be possible.

The length of the seed filling period has been shown to be positively correlated with final seed yield by a number of researchers (Hanway and Weber, 1971; Dumphy and Green, 1979; Gay et al., 1980; McBlain and Hume, 1980; Boote, 1981; Nelson, 1986; Smith and Nelson, 1986; Egli et al., 1984; Egli, 1994). However, in simulation and field grown studies, Salado-Navarro et al. (1986) observed that the correlation between yield and seed filling duration estimates were, generally non-significant and inconsistent. The time period in which the seed filing period occurred may have contributed to this lack of correlation. If the reproductive period is lengthened by earlier flowering so that plants enter the reproductive period when the days are longer it would have a greater positive effect on yield than if the reproductive period is lengthened by later maturing of the soybeans, when the days are much shorter. In a shade stress test comparing soybean varieties of different maturity, Egli (1997) concluded that yields of both early and late cultivars were determined primarily by environmental conditions during reproductive growth. A major factor contributing to higher soybean yields from earlier planting has been attributed to the greater insolation during the reproductive period (Egli and Bruening, 1992). These results indicate lengthening the reproductive period by initiating the reproductive period earlier in the growing season when the light intensity is higher and the days are longer would significantly increase the yield potential of soybeans.

Spaeth et al. (1987) conducted a study in Japan to assess the interaction of temperature, radiation, and duration of crop growth in the determination of seed yields, by comparing simulations and observed data. They concluded that in their study, conducted in 750 mm row spacing, that the higher early season temperatures stimulates more rapid leaf area development and canopy closure. Thus more of the high radiation levels earlier in the growing season are intercepted, resulting in higher seed yield. However in narrower rows, 175–190 mm row spacing, where the canopy closure is much quicker, this effect would be expected to be less of a factor. The effect of the early season higher temperature on the onset of the reproductive period (time of flowering) in these studies was not reported.

The purpose of this paper is to document the effect of higher than normal, early spring temperatures on the yield potential of soybeans grown in a maximum yield environment, and to provide evidence for a delayed flowering barrier to higher soybean yields in higher latitudes. Results from these studies suggest that in most years the delayed flowering of full season soybean varieties is a major yield limiting factor in soybeans and that earlier flowering could significantly increase the yield potential of soybeans.

2. Materials and methods

Two one-half hectare fields with good surface and subsurface drainage [Wooster silt loam soil (fine-loamy, mixed mesic Typic fragiudalf)] were established as soybean maximum yield fields at the Ohio Agricultural Research and Development Center, Wooster, OH (40°N, 82°W) in 1977. The objective of maximum yield research is to remove as many manageable yield limiting factors as possible, regardless of cost or practicality, to determine the yield potential of soybeans and to identify yield limiting factors. Two adjacent fields were selected so a 2-year corn/soybean rotation could be established to minimize disease build up. A solid set sprinkler irrigation system with sprinkler nozzles spaced 6.6 m apart in a square pattern to match the 6.6 m plot length was used. Once in place, applications of 50 mm of water (rainfall plus irrigation) were applied weekly to minimize water as a yield limiting factor. Preplant applications of 1120 kg/ha of 0–18–36 fertilizer and 672 kg/ha of 33–0–0 were made annually to minimize P, K, and N as possible yield limiting factors.

The yield plots were 3 m × 6.6 m, end trimmed at maturity to a harvest length of 4.8 m. From 1977 to 1988, ten 175 mm spaced rows were used, harvesting the center six rows for yield. Since 1989, a skip row system has been used with six 187.5 mm spaced rows with one border row on each side spaced 656 mm from the six 187.5 mm spaced harvest rows, with 750 mm between plots, for a total plot width of 3 m. Yield was computed based on a harvest plot width of 1.5 m. These plots are planted from a single seed packet using a grain drill that equally divides the seed into ten equal rows. The outside two rows on each side are combined into a single unit giving border rows with a double seeding rate. This system permits the direct harvest of the six harvest rows with a plot combine without the necessity of hand-trimming off the border rows.

Because of the lodging problem with the taller indeterminate cultivars, mostly determinate semidwarf (*dt1e1*) cultivars and breeding lines have been used in the maximum yield test with a seeding rate of 750,000 seeds/ha of 90%+ germ seed. Where indeterminate (*Dt1e1*) varieties were included, a 562,500 seeds/ha rate was used. During the first 5 years, 1977–1981, no fungicide treatment was used, but it was observed that with the weekly sprinkler irrigation application severe Septoria brown spot (*Septoria glycines* Hemmi) developed on some cultivars, resulting in premature defoliation and a significant yield reduction (Cooper, 1989b). Thus, beginning in 1982, routine benomyl (methyl-1-(butylcarbamoyl)-2-benzimidazole carbamate) fungicide applications were made to control foliar diseases. Also insect feeding necessitated the use of insecticides. To maximize yields, early planting was used each year (1 May, + or −5 days).

This standard procedure was used in the maximum yield research plots every year, 1982–1999. Yet the test average yield varied from 3600 to 6000 kg/ha and the yield of the highest yielding individual entry in the test varied from 4200 to over 7000 kg/ha, depending on the year. It was noted that the higher yielding years tended to be associated with unusually early warm spring temperatures that resulted in the soybeans flowering up to 2 weeks earlier than normal. To test this relationship, the regression of the test average yield on average May temperature was computed.

3. Results and discussion

The year to year variation in test average yield and the yield of the 10 highest yielding lines is shown in Table 3.

After several years of attempting to duplicate the high yields (6000–7000 kg/ha) reported in farmer yield contests, in 1982 this goal was achieved. The overall average yield of 54 entries was 5956 kg/ha with four semidwarf cultivars producing yields in excess of 6670 kg/ha. Having developed a cultivar/production system (semidwarf cultivars planted in 175 mm row spacing at a seeding rate of 750,000 seeds/ha, combined with high fertility, weekly irrigation, and pest control that resulted in these high yields), it was anticipated that these high yield levels could be obtained routinely.

In 1983, however, using the same maximum yield production system, the test average yield was 4549 kg/ha with highest individual entries yields of 4662–5316 kg/ha. In 1984 similar yields were obtained. In 1985, yields were again high with a test average yield of 5549 kg/ha and individual lines yielding from 5483 to 6710 kg/ha. But in the subsequent 12 years, 1986–1997, these high yields could not be duplicated, even though all manageable yield limiting factors, including weekly irrigation to remove water as a yield limiting factor, were minimized. The test average yields over this period ranged from 3575 kg/ha in

Table 3
Year to year variation in yield of the 10 highest yielding lines under a maximum yield soybean production system, Wooster, OH

Entry	Yield (kg/ha)	Entry	Yield (kg/ha)
1982[a]			
HC78-1931	7050	Pixie	6603
HC78-1884	6823	HC79-1737	6590
HC79-1644	6770	HC78-349	6530
HC78-352	6677	Sprite	6510
HC78-1318	6643	HC78-354	6503
1983[b]			
HC78-350	5316	Asgrow 3127	4869
HC78-279	4989	HC78-353	4816
Sprite	4949	HC78-352	4729
Williams 82	4949	HC78-349	4722
HC78-265	4889	HC76-1391	4662
1984[c]			
HC80-1944	5516	HC78-352	4989
HC78-353	5483	HC78-350	4896
Asgrow 3127	5229	Pixie	4836
HC78-354	5136	Williams 82	4696
Sprite	5102	HC78-1884	4642
1985[d]			
Sprite	6710	Hobbit	5783
HC80-592	6283	Asgrow 3127	5683
HC80-585	5983	Pella	5663
HC78-523	5956	HC80-1944	5489
HC80-1942	5863	HC74-634RE	5483
1992[e]			
HC86-3403	4249	Thorne	3929
HC89-2237	4189	HC88-4257	3922
HC89-52	3975	HC87-3299	3909
HC88-11	3942	Flyer	3875
Edison	3935	HC87-6037	3869
1993[f]			
H87-2154	5529	H87-3299	5296
Flyer	5429	H89-2233	5216
H89-868	5389	HC88-11	5216
HC85-2176	5336	H89-2232	5169
Resnik	5329	H89-391	5163
1998[g]			
Stalwart	6050	Strong	5930
HC95-261PR	6043	HC95-259PR	5870
HC94-380-4	5956	HC94-419-6	5830
HC94-1946-19	5956	Charleston	5816
HC94-168	5943	Stout	5790
1999[h]			
Stout	6443	HC95-1597	6003
HC94-1382	6270	Stalwart	5983
HC95-634-10	6210	HC94-1065	5963
HC92-984	6210	HC95-4337	5903
HC95-2137-4	6203	HC95-2005	5843

[a] Mean yield of 54 entries: 5956 kg/ha.
[b] Mean yield of 24 entries: 4549 kg/ha.
[c] Mean yield of 24 entries: 4602 kg/ha.
[d] Mean yield of 23 entries: 5549 kg/ha.
[e] Mean yield of 52 entries: 3575 kg/ha.
[f] Mean yield of 48 entries: 4862 kg/ha.
[g] Mean yield of 64 entries: 5383 kg/ha.
[h] Mean yield of 59 entries: 5416 kg/ha.

1992 to 4862 kg/ha in 1993 with highest individual entry yields in the 4200–5500 kg/ha range.

Based on these results, the objective became to determine if there was something unique about 1982 and 1985 that contributed to the exceptionally high yields. Variation in rainfall from year to year could largely be eliminated as a factor because of the weekly irrigation begun around the middle of June and continued to maturity. The unique factor about these 2 years was that both years had exceptionally early warm spring temperatures that resulted in flowering approximately 2 weeks earlier than normal (15 June vs. 1 July). It was postulated that this earlier initiation of the reproductive period in mid-June, when the light intensity (sun angle) is highest and the days are longest (greatest total solar radiation is available), may have contributed to these exceptionally high yields. Also, since maturity was similar to normal years, the reproductive period was lengthened.

In 1998, the opportunity occurred to test this hypothesis. The early spring temperatures were exceptionally high and the soybean entries in the trial initiated flowering in mid-June, approximately 2 weeks earlier than normal. Based on this information it was predicted record yields would again be obtained. The test average yield was 5383 kg/ha with the highest yielding individual entries producing over 6000 kg/ha yields. Similar early warm spring temperatures and early flowering occurred again in 1999, resulting in a test average yield of 5416 kg/ha and the six highest yielding lines producing over 6000 kg/ha.

These results strongly support the hypothesis that the exceptionally high yields in 1982, 1985, 1998, and

1999, were due to the early warm spring temperatures that triggered earlier flowering in the soybeans. Conversely, the lower yields in 1983–1984 and for the years 1986–1997 could be attributed to the delayed flowering that occurs under more normal spring temperatures.

These results indicate there is a strong interaction between photoperiod and early spring temperatures, a photo/thermal effect. Early warm spring temperatures interact with the photoperiod to stimulate earlier flowering in soybeans. This lengthens the reproductive period when the available light energy is greatest (highest light intensity and longest days) in higher latitudes.

At Wooster, OH, the average 24 h total solar radiation declines from 474 Langleys (cal/cm^2) in June to 351 Langleys in September. The maximum daily solar radiation declines from 680 Langleys (15–30 June) to 444 Langleys (15–30 September).

As a result, in a maximum yield environment where other yield limiting factors are minimized, the yield potential of soybeans is increased from the 4500 to 5500 kg/ha level to a yield level of 6000–7000 kg/ha.

To measure the relationship between early spring temperatures and soybean yield potential, the regression of the test average yield on average May temperature was computed over the 18-year period from 1982 to 1999, using the yield data from the continuous maximum yield research plots at Wooster, OH, and the long term, on site weather records. The availability of the long term maximum yield data was essential for testing this relationship. Without other yield limiting factors being minimized (water, lodging, disease, etc.), any relationship between early spring temperatures and yield would be confounded by other yield limiting factors that vary from year to year.

When the data from all 18 years are included (Table 4), the r-value of the regression analysis (0.041), was non-significant (Table 5). The major reason for this lack of significance could be attributed to 2 years, 1991 and 1987, when factors other than early spring temperature limited the yield.

The highest average May temperature occurred in 1991, but the average test yield was the lowest. Examination of the data and weather records provide an explanation for this apparent aberrant relationship between average May temperature and average test yield. A severe drought in early June (10 mm from 1 to 20 June, before irrigation was initiated) combined with early flowering, triggered by the high average May temperatures, resulted in many of the determinate semidwarf soybean cultivars being very short (300–400 mm tall compared to a normal height of 500–750 mm tall in an irrigated environment). This severely limited their yield potential. Because of their determinate characteristic, semidwarf cultivars must reach their full height by flowering. The early flowering triggered by the high May temperature, combined with the early June drought, did not allow the semidwarf cultivars to reach adequate height before flowering. Had irrigation been applied in early June to enable the semidwarf cultivars to produce more normal plant

Table 4
Average May temperatures and soybean average test yields at the maximum yield test site, Wooster, OH, 1982–1999

Year	Average May temperature (°C)	Average test yield (kg/ha)
1982	17.6	5956
1983	13.0	4549
1984	12.9	4602
1985	15.9	5549
1986	16.4	4756
1987	17.0	4276
1988	15.7	3982
1989	13.9	4095
1990	13.8	4015
1991	19.4	3442
1992	14.1	3575
1993	15.2	4862
1994	12.9	4215
1995	14.8	4716
1996	14.6	4642
1997	11.9	4756
1998	18.2	5383
1999	16.5	5416

Table 5
Regression of average test yield with average May temperature at the soybean maximum yield test site at Wooster, OH, 1982–1999

Year	r^2	Regression	P
All 18 years	0.041	kg/ha = 67.0 °C + 3580	0.427
w/o 1991	0.293	kg/ha = 188.2 °C + 1851	0.025
w/o 1991 + 1987	0.387	kg/ha = 222.9 °C + 1384	0.010

Fig. 1. Comparison of test average soybean yields (kg/ha) and average May temperatures (°C) under a maximum yield soybean production system, Wooster, OH, 1982–1999.

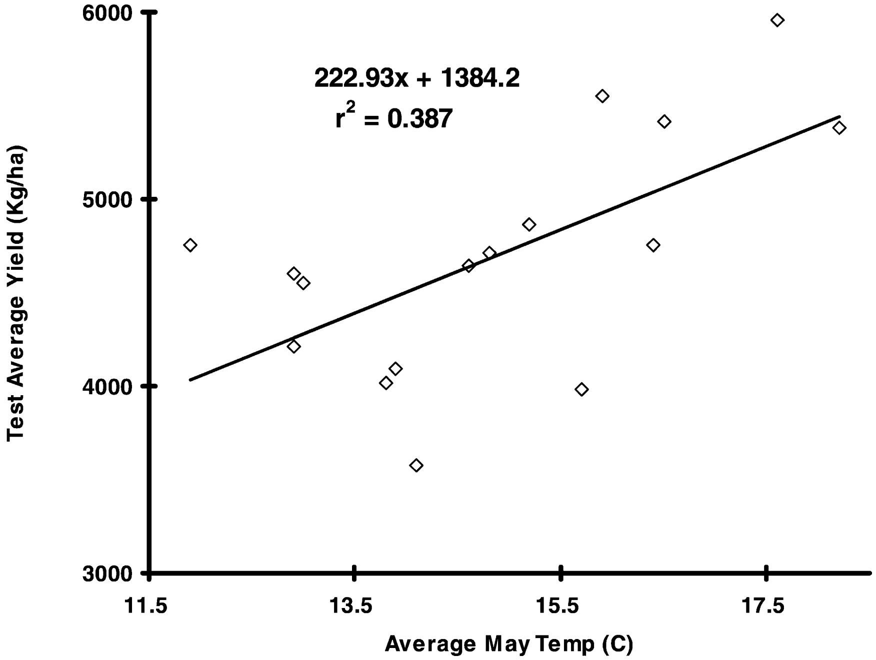

Fig. 2. Regression of test average soybean yields (Y) on average May temperatures (X) in a maximum yield environment, Wooster, OH, 1982–1999.

height, it is postulated that record yields would have been obtained in 1991 because of the earlier flowering.

When the 1991 data are excluded, the regression of the average test yield (kg/ha) on the average May temperature (°C) is kg/ha $= 188.2\,°C + 1851$ with and *r*-value of 0.293 (Table 5), indicating a significant relationship between average May temperature and soybean yield.

The other apparent aberrant data occurred in 1987 where the average May temperature ranked fourth highest over the 18 years, but the average test yield ranked 12th (Table 4). Severe defoliation from a foliar disease occurred, caused by an *Alternaria* sp. that was apparently resistant to the fungicide, resulting in a significant reduction in the average test yield.

When both the 1991 and 1987 data are deleted, the regression of the average test yield on the average May temperature is kg/ha $= 222.9\,°C + 1384$ with an *r*-value of 0.387 (Table 5). Plotted over these 16 years, the relationship between the average May temperature and average test yield is shown in Fig. 1. The regression of the test average yield on the average May temperature is shown in Fig. 2.

These results indicate there is a major delayed flowering barrier to higher soybean yields in the higher latitudes of the US. Normal spring temperatures result in delayed flowering which limits soybean yields to the 4500–5500 kg/ha range. Earlier flowering which takes advantage of the higher light intensity and longer days in mid- to late-June, and lengthens the reproductive period, can increase the yield potential of soybeans to the 6000–7000 kg/ha range when other yield limiting factors are minimized. These results suggest there is a major opportunity to increase the yield potential of soybeans grown in the higher latitudes by breeding for full season cultivars that will bloom earlier under normal spring temperatures.

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